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U. of Iowa 65-43

Spatial Distribution and Time Decay of the Intensities of Geomagnetically Trapped Electrons from the High Altitude Nuclear Burst of July 1962*

by

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ABSTRACT

A one-year observational study of the artificial radiation belt produced by the nuclear burst Starfish on 9 July 1962 is reported. It is estimated that 1.3×10^{25} electrons from radioactive fission products, or some 2.6 % of the total yield, were present in geomagnetically trapped orbits at 10 hours after the burst. These electrons disappeared in the manner expected from the atmospheric loss theory of Walt for values of the magnetic shell parameter $L < 1.25$ earth radii. At increasing values of L the rate of disappearance was progressively more rapid than expected by this theory. The maximum observed value of the apparent mean lifetime of ~ 2 MeV electrons in the time range $4000 < \Delta t < 10{,}000$ hours was 2 years at $L = 1.5$. About 15% of the initially injected electrons (or 0.4 of 1% of the total) survived the first $5\frac{1}{2}$ months, about 10% the first year.

Detailed spatial distribution and temporal data are given in a series of plots.

Introduction

Störmer [1907] discussed the dynamical motion of an isolated, electrically-charged particle in the field of a point magnetic dipole and showed that, under specified conditions, it is possible for a particle to be trapped in such a field with its spiraling, drifting trajectory forever confined within a toroidal region which is a figure of revolution about the axis of the dipole.

In October 1957 Christofilos [1959] suggested the possibility of artificially populating a Störmer region around the earth with beta-rays from the radioactive fission products of a nuclear bomb, exploded at high altitude. Such a populated region is now known as a "radiation belt". Following the discovery in early 1958 [Van Allen, 1958] that the region around the earth already contained large intensities of charged particles from natural sources, it was decided to proceed with a series of experiments of the type envisoned by Christofilos. These experiments were conducted in August and September 1958 and resulted in the successful production of artificial radiation belts. Extended publication of the results has been made [Scientific Effects of Artificially Introduced Radiations at High Altitudes, Journal of Geophysical Research 64, 865-938, 1959].

In the period 1958-1962, there was created a total of nine artificial radiation belts which remained detectable for periods greater than one day in the presence of the natural radiation belts of the earth. All of these were produced by high-altitude nuclear bombs, six by the United States and three by Russia, and all have been observed by satellite equipment prepared in the author's laboratory as well as by an increasing variety of satellite and other equipment prepared in other laboratories in the United States, Canada, Russia, England, and elsewhere. Table I gives an abridged summary.

The purpose of the present paper is to summarize the observations by satellites Injun I, Injun III, and Explorer XIV of the Starfish radiation belt which was produced on 9 July 1962. Comprehensive review of the literature is not attempted in this brief paper, though references to other work are given wherever directly pertinent.

Table I. Artificial Radiation Belts 1958-1962

Designation	Date of Burst	Altitude km	Nominal Explosive Yield TNT Equivalent	Maximum Omnidirectional Intensity at t=0, $(cm^2\ sec)^{-1}$	L Value of Burst	Apparent Mean Lifetime (Approx.)
Teak	1 August 1958	~ 75	10 megatons	10^3	1.1	Few days
Orange	12 August 1958	~ 45	10 megatons	10^3	1.1	Few days
Argus I	27 August 1958	~ 200	1.4 kilotons	10^5	1.7	3 weeks
Argus II	30 August 1958	~ 250	1.4 kilotons	10^5	2.1	3 weeks
Argus III	6 September 1958	$\gtrsim$ 480	1.4 kilotons	10^6	2.0	1 month
Starfish	9 July 1962	~ 400	1.4 megatons	10^9	1.12	1.5 years
U.S.S.R. I	22 October 1962	Unknown	"Submegaton"	10^7	1.9	1 month
U.S.S.R. II	28 October 1962	Unknown	"Submegaton"	10^7	2.0	1 month
U.S.S.R. III	1 November 1962	Unknown	"Megaton"	10^7	1.8	1 month

<u>Data on the Starfish Nuclear Burst</u>

Publicly available data on the Starfish nuclear burst are:

(a) That it occurred at 09:00:05 U.T. on 9 July 1962 at an altitude of about 400 kilometers;

(b) That the geographic position was near Johnston Island (geographic coordinates 16.7° N, 190.5° E);

(c) That, from the above data, the position in trapped particle coordinates was B = 0.29 gauss, L = 1.12 earth radii;

(d) That the explosive yield was 1.4 megatons TNT equivalent; and

(e) That the nominal total yield of fission-decay electrons was 5×10^{26}.

Observations with Injun I, Injun III, and Explorer XIV

Three previous papers have been published [O'Brien, Laughlin, and Van Allen, 1962] [Van Allen, Frank, and O'Brien, 1963] [Van Allen, 1964] and several further University of Iowa research reports have been circulated privately.

The University of Iowa--Office of Naval Research satellite Injun I was launched on 29 June 1961 into an orbit with perigee altitude 890 km, apogee altitude 1010 km, inclination 67°, and period 104 minutes. Useful data were received from launch until latter August 1962. Thus a special virtue of the Injun I observations is that extensive pre-Starfish measurements were available from the same detectors in the same satellite as were post-Starfish measurements for over a month after the burst. Hence, it is possible to study the incremental effect of the burst with a confident knowledge of the pre-burst "background" due to natural radiation.

The series of observations was resumed with the launching of the U. of Iowa--ONR satellite Injun III on 13 December 1962 into an orbit having the following initial parameters: perigee altitude 237 km, apogee altitude 2785 km, inclination 70.4°, and period 116.2 minutes. This satellite carried a variety of particle detectors including one nominally identical to one in

Injun I. Observations with Injun III continued to early October 1963.

Additional data of value were obtained with U. of Iowa equipment on the NASA satellite Explorer XIV, launched on 2 October 1962 into a very eccentric orbit having the following initial parameters perigee altitude 282 km, apogee altitude 98,533 km, inclination 33°, and period 36.4 hours. Useful data were obtained over a ten-month period.

A further continuation of the long term study of the decay of the Starfish radiation belt was begun on 21 November 1964 with Injun IV and is continuing over a year later. Results from Injun IV will be reported at a later date.

Detectors

Detectors designated SpB on Injun I and Injun III were small Geiger tubes having an effective cross-section for penetrating particles (galactic cosmic rays) of ~ 0.12 cm^2, averaged over direction. The shielding of the counting volume was complex in detail but over some 3π steradians is estimated to be effectively as follows: 0.3 g cm^{-2} of magnesium, silicon and glass, 3.5 g cm^{-2} of lead, and 0.4 g cm^{-2} of steel in the order given starting from the outside. The remaining solid angle was shielded by a miscellany of equipment totalling some tens of g cm^{-2}.

The SpB detector counts fission-product decay-electrons via the bremsstrahlung which is produced when they are stopped in the shield [Petschek, 1963] [Van Allen, Frank, and O'Brien, 1963]. The ratio ϵ of the counting rate of the tube R in counts sec^{-1} (corrected for dead time when necessary) to the omnidirectional intensity J_o in cm^{-2} sec^{-1} has been calculated [L. A. Frank, private communication] for isotropic exposure to monoenergetic electrons and is plotted as a function of electron energy E in Figure 1. Also shown in Figure 1 is the differential energy spectrum of electrons from the thermal neutron fission of U^{235}, measured in approximate secular equilibrium by Carter, Reines, Wagner, and Wyman [1959], designated dN/dE; and the product

ϵ dN/dE. Thus, it is clear that the sensitivity of SpB to a fission electron-spectrum is concentrated in the approximate energy range 1 to 5 MeV.

The calculated mean value of ϵ for the fission spectrum (from the data of Figure 1) is 6×10^{-6}. Three different experimental determinations give somewhat higher values. The direct in-flight determination and a Sr^{90} calibration are described in Van Allen, Frank, and O'Brien [1963]. A subsequent laboratory calibration using machine-generated beams of monoenergetic electrons has been made over the energy range 0.4 to 2.4 MeV by R. J. Farmer of the Ling-Temco-Vought Company. On the basis of these various determinations I have adopted the relation:

$$\epsilon = \frac{R}{J_o} = 1.0 \times 10^{-5}$$

for the fission spectrum. The estimated uncertainty in ϵ is some 50%. The form of the dependence of ϵ on E as shown in Figure 1 has been used for estimates on spectra which evolve as atmospheric losses modify the initial spectrum.

Most of the curves and data of the present paper are in terms of the true counting rate R of the SpB.

During the flight period of Injun III a larger, lightly shielded Geiger tube, designated 302, became useful. Its detection efficiency curve is approximated by zero efficiency below 1.8 MeV

and unit efficiency with an effective area of 0.5 cm^2 above 1.8 MeV for the fission spectrum (direct penetrations).

Observations

Observed data were segmented into time eras of length varying from a day early in the history of the artificial belt to three months later on. Counting rates for each era were entered on a large sheet of rectangular graph paper at points having the calculated values of magnetic shell coordinates B and L at the positions in space at which they were observed. Smooth contours of constant counting rate were drawn by hand through the array of data and were taken to represent the situation for the era.

From these basic graphs a number of other presentations of the data were derived:

(a) Counting rates versus B at selected values of L for each era.

(b) Counting rates versus L at selected values of B for each era.

(c) Counting rates versus time at selected values of B and L.

(d) Contours of constant counting rate in R, λ space.

In the figures which follow Δt is the elapsed time measured from 09:00 U.T. on 9 July 1962.

Figures 2, 3, 4, 5, 6, and 7 give time decay data from Injun I. The pre-burst background has been subtracted. Open squares and solid circles are used alternately to distinguish

adjacent curves. According to Filz and Holeman [1965] there was a significant impulsive increase in the intensity of 55 MeV trapped protons at low altitudes over the South American magnetic anomaly ($L \sim 1.4$) at the time of the Starfish burst. A correction for this effect (not shown here) will result in a steeper rate of decay of the curves of Figures 2-7, the correction being significant for the highest B-value member of each of the families of curves in Figures 3, 4, and 5 and probably negligible elsewhere.

Since the spectrum of trapped electrons from an impulsive source varies with time, the characteristic of the SpB detector (Figure 1) should be borne in mind in the interpretation of the time decay curves.

The time history of the artificial radiation belt is continued in Figures 8, 9, 10, 11, 12, and 13 in which data from Injun I and Injun III have been plotted on the same graphs assuming that the absolute sensitivities of the respective SpB detectors are identical. The effective omnidirectional factor of the detector on Injun III (for counting penetrating particles) was found to be 1.5 to 1.9 times as great as that of the one on Injun I by comparing galactic cosmic ray counting rates at high latitudes. Thus it is probable that normalization of the two sets of data would result in somewhat steeper decays

during the period $1200 < \Delta t < 4000$ hours than those shown. I have not made this normalization on the grounds (a) of its uncertain applicability to the counting of non-penetrating electrons via their bremsstrahlung and (b) of other undetermined uncertainties of the order of unity due to slightly different instrumental environments of the respective detectors on the two different satellites.

In Figures 8, 9, 10, 11, 12, and 13 total counting rates are plotted and the pre-Starfish Injun I background rates are shown by horizontal bars at the right hand side of the graphs.

In Figure 14 are shown iso-counting-rate contours on a B-L diagram from Injun I for the year preceding the Starfish burst (plus an extension of the 800 count/sec contour with Pioneer IV, March 1959 data) and from Injun III at $\Delta t \sim 4050$ hours. Two other sets of contours from Injun III data are shown in Figures 15 and 16.

Summary

(a) In Figure 17 are shown meridian cross-sections of the Starfish radiation belt for two different eras, in R, λ coordinates. The diagrams are obtained by coordinate transformation from the basic B-L plots to equivalent polar coordinate R, λ space. The solid portions of the contours are those observed directly; the dashed portions of the contours in the left hand diagram are obtained by extrapolation to the equator in B-L space. As viewed in Figure 17, the extrapolation process appears to permit considerable uncertainty in the outer portion of the belt. However, in consideration of the fact that electrons from radioactive fission products must be injected isotropically at the point of decay, there is a calculable dependence of J_o on B for L = constant corresponding to any assumed distribution of decays [Van Allen, 1962]. On these considerations it is found to be effectively impossible to obtain a substantially different outer boundary for the $\Delta t = 10$ hour distribution by extrapolation of Injun I contours in B-L space. Hence our results are thoroughly irreconcilable with the widely published diagram of Hess and Nakada [1962] [cf. Van Allen, Frank, and O'Brien, 1963], insofar as the latter was represented as showing the distribution of fission-decay

electrons. Brown and Gabbe [1964] have, however, shown persuasive evidence for an outer fringe (higher L values) of the basic belt of "hard" electrons (Figure 17) caused by the burst in some secondary manner and comprised of electrons having a much softer energy spectrum than that of fission decay electrons.

(b) The volume integration of the left hand diagram of Figure 17 gives a total inventory of fission-decay electrons of

$$1.3 \times 10^{25}$$

in trapped orbits at $\Delta t = 10$ hours. This volume integration corresponds to an "injection efficiency" of 2.6 %. The overall uncertainties in this estimate are such as to make it quite unlikely that the true value lies outside of the range 2 to 5%.

(c) The "apparent mean lifetime" τ of ~ 2 MeV trapped electrons has been taken from the linear portions of decay curves similar to Figures 8, 9, 10, 11, and 12 for $1.15 < L < 1.4$ for the time period $4000 < \Delta t < 10{,}000$ hours. Additional values at $L = 1.4$ and $L = 1.5$ have been derived from the 302 data of Injun III. Note that these values of τ are independent of the uncertainty in relative sensitivities of the SpB detectors in Injun I and Injun III. In the range $2.1 < L < 3.6$ a series of comparable values of "apparent

mean lifetime" are available from observations with Explorer IV of the artificial radiation belt of Argus III [Van Allen, McIlwain, and Ludwig, 1959] and from observations with Explorer XIV of the three artificial radiation belts produced by Russian high altitude nuclear bursts in October-November 1962 [Frank, Van Allen, and Hills, 1964]. A summary plot of all of these values of τ is given in Figure 18 [Van Allen, 1964]. A maximum value of about 2 years occurs at $L \sim 1.5$.

(d) Walt [1964] has achieved an essentially complete understanding of the time decay data shown herein for $L < 1.25$ on the basis of elementary processes of scattering and energy loss of electrons in the quiescent atmosphere.

(e) For L increasing above 1.25 the observed values of τ fall below the expected theoretical curve of Walt in a progressively more dramatic way (Figure 18), a result well known for many years from observation of the time variations of the natural outer radiation belt of the earth.

(f) The maximum value of the observed lifetime is about fifty times less than that predicted by Lovell, Hess, and others in the late summer of 1962.

(g) Of the some 2.6% (2 to 5%) of the total number of fission decay electrons from the Starfish burst which were trapped at

$\Delta t \sim 10$ hours, about 15% (or 0.4 of 1% of the total) survived the first $5\frac{1}{2}$ months and about 10% the first year.

Acknowledgement

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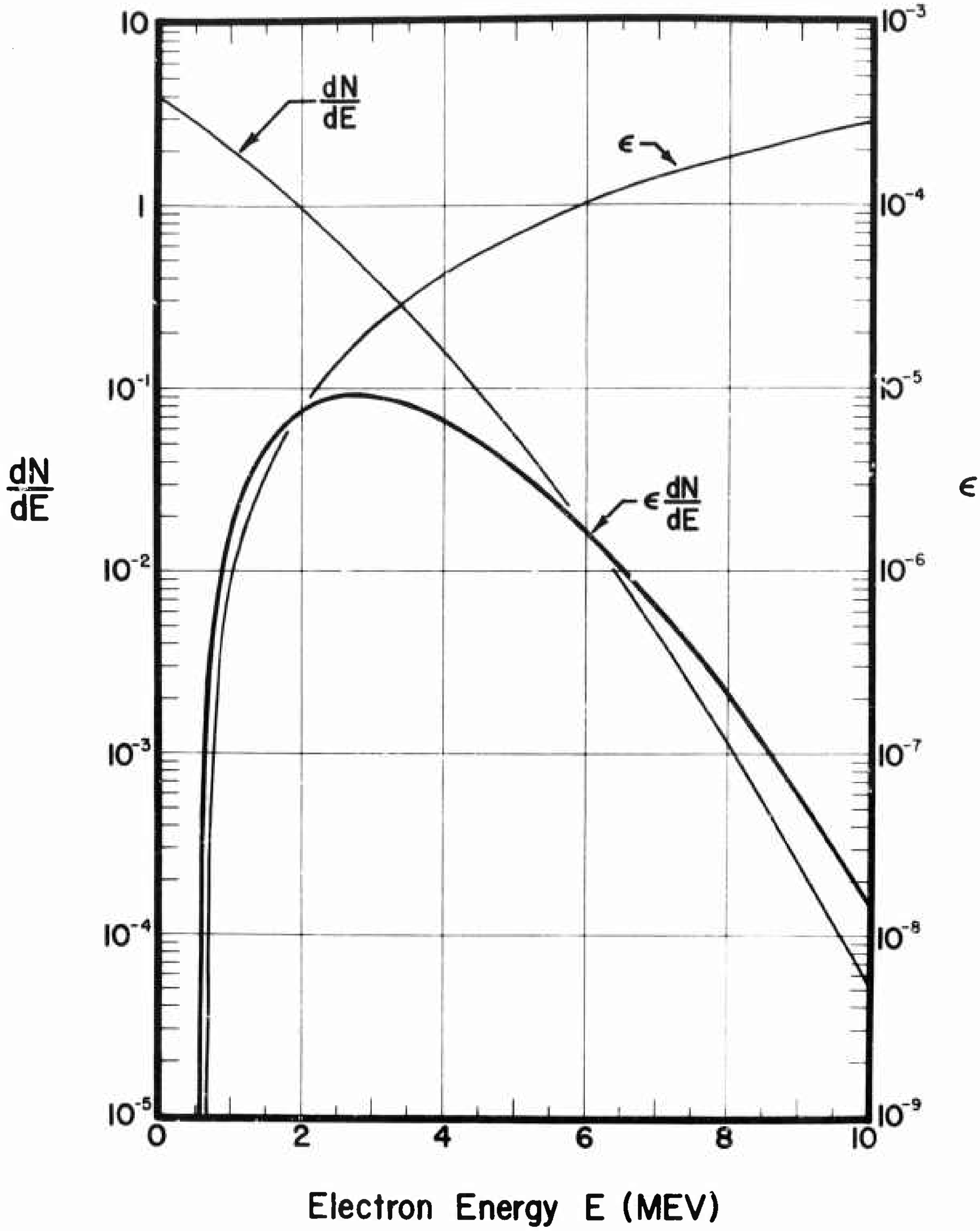


10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$\frac{dN}{dE}$
ϵ
$\epsilon \frac{dN}{dE}$
$\frac{dN}{dE}$
ϵ
0
2
4
6
8
10
Electron Energy E (MEV)

Figure 1

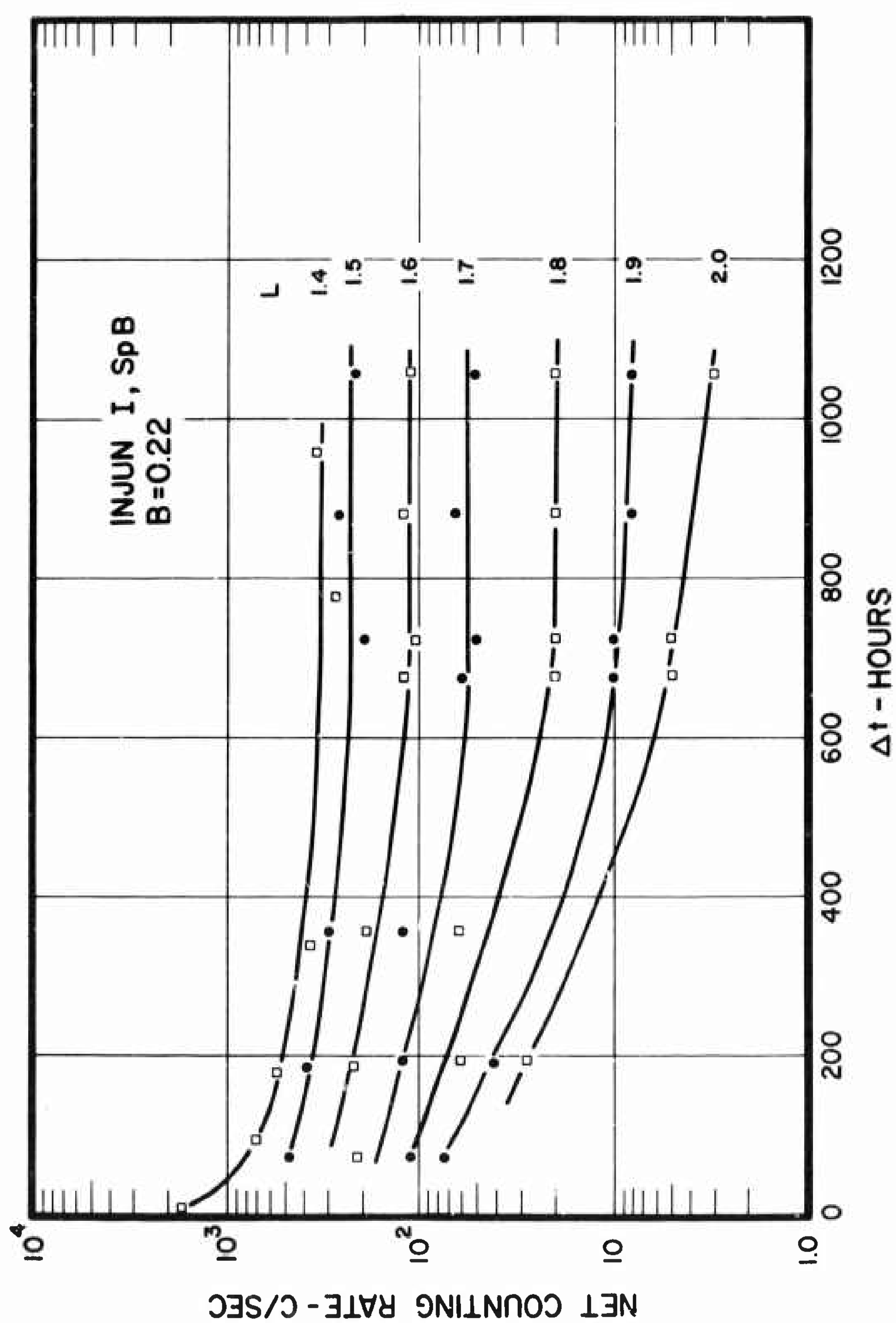
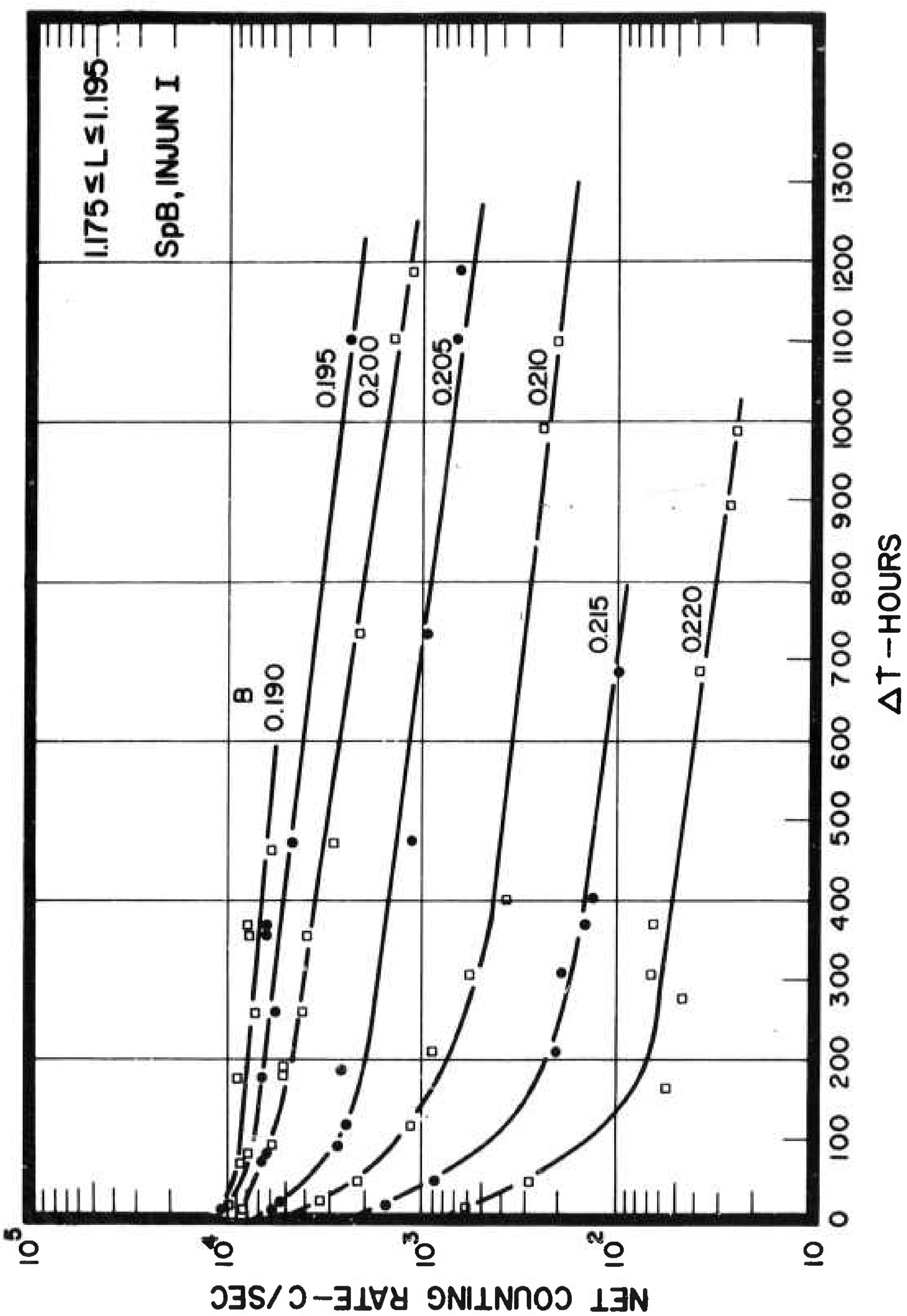
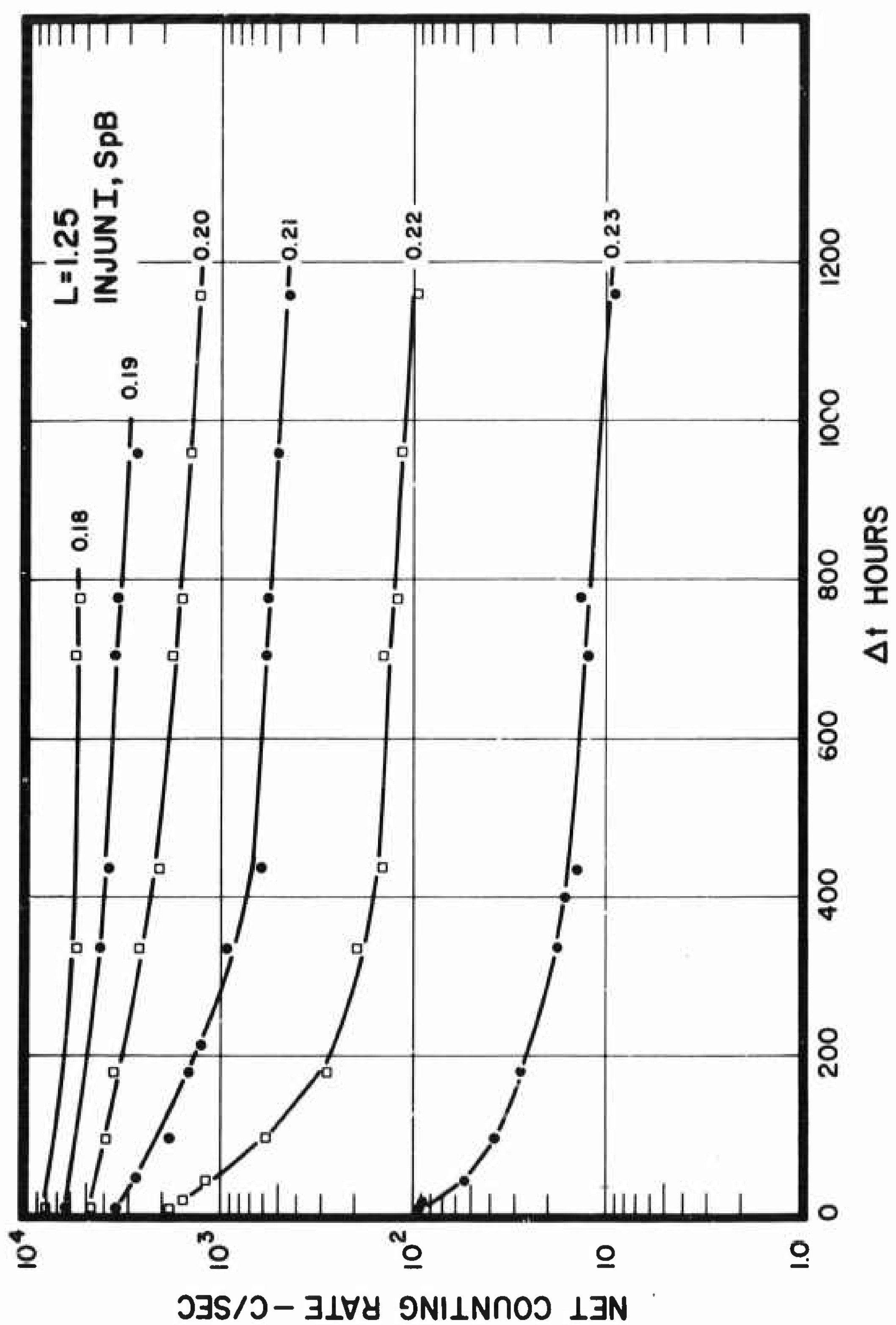

INJUN I, Sp B
B=0.22
L
1.4
1.5
1.6
1.7
1.8
1.9
2.0
0
200
400
600
800
1000
1200
Δt - HOURS
10^4
10^3
10^2
10
1.0
NET COUNTING RATE - C/SEC

Figure 2



1.175 ≤ L ≤ 1.195
SpB, INJUN I
B
0.190
0.195
0.200
0.205
0.210
0.215
0.220
ΔT – HOURS
NET COUNTING RATE – C/SEC
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
10
10^2
10^3
10^4
10^5

Figure 3



L=1.25
INJUN I, SpB
0.18
0.19
0.20
0.21
0.22
0.23
NET COUNTING RATE – C/SEC
10^4
10^3
10^2
10
1.0
Δt HOURS
0
200
400
600
800
1000
1200

Figure 4

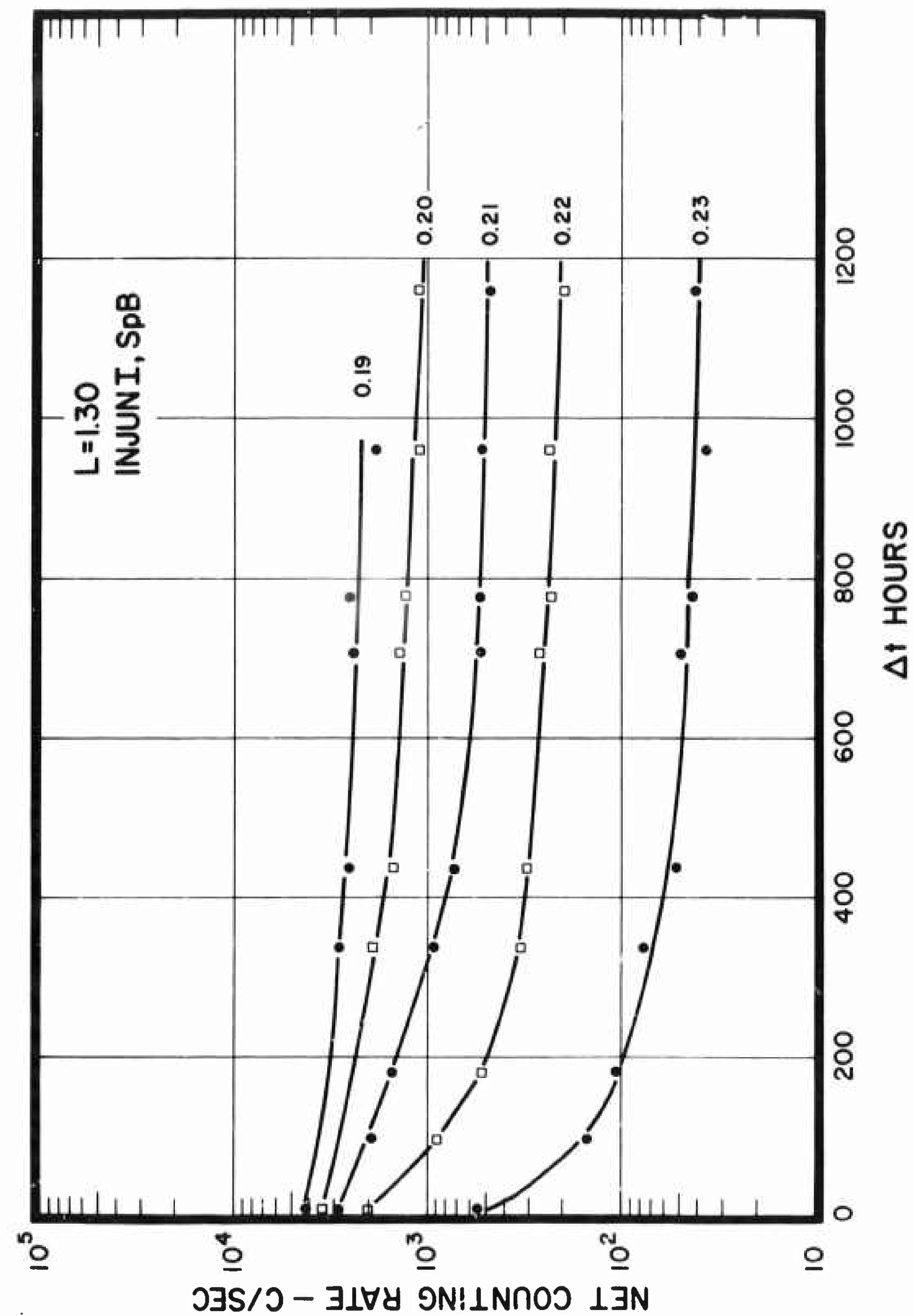
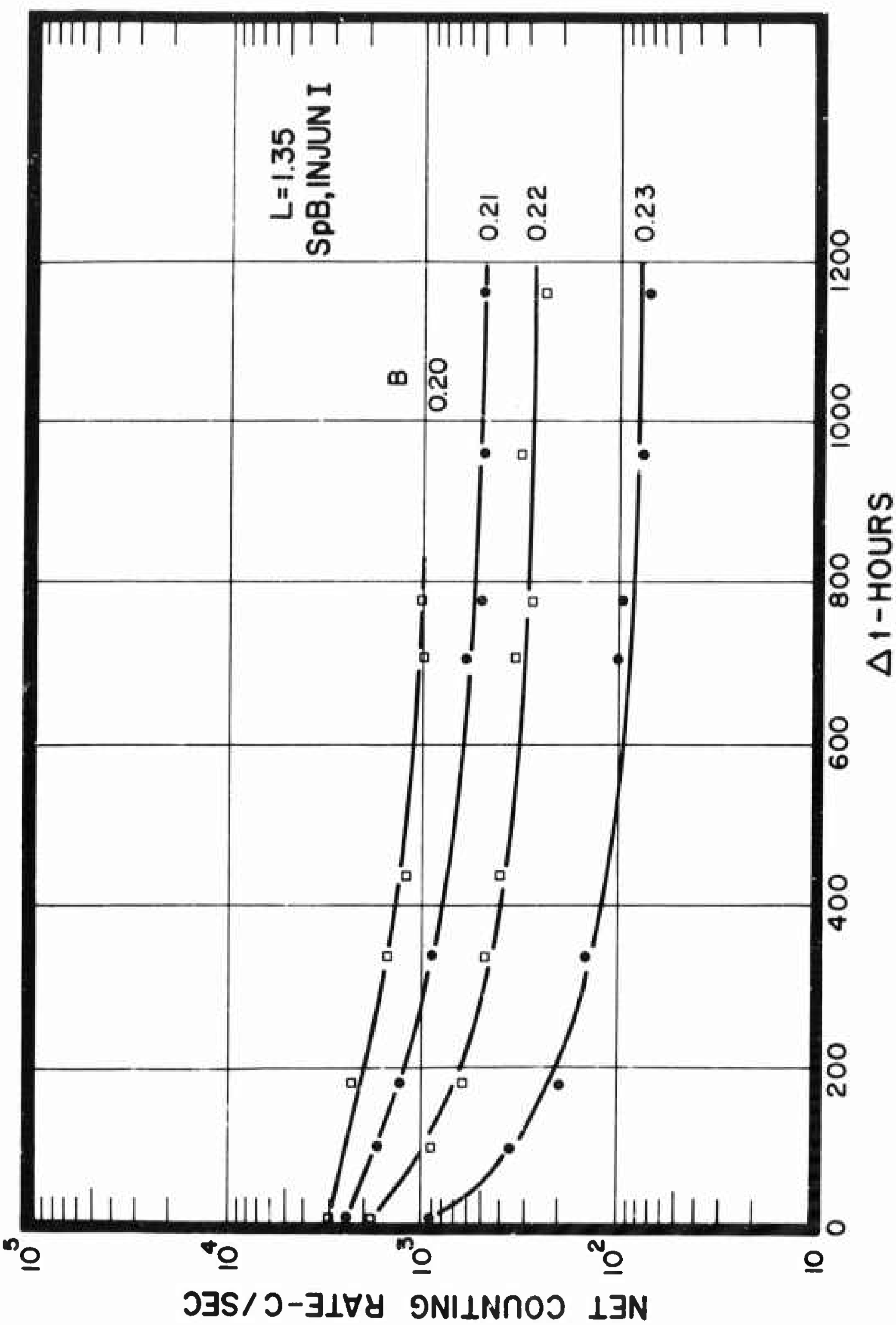

L=1.30
INJUN I, SpB
0.19
0.20
0.21
0.22
0.23
NET COUNTING RATE – C/SEC
10^5
10^4
10^3
10^2
10
0
200
400
600
800
1000
1200
Δt HOURS

Figure 5



L=1.35
SpB, INJUN I
B
0.20
0.21
0.22
0.23
NET COUNTING RATE-C/SEC
Δt-HOURS
0
200
400
600
800
1000
1200
10
10^2
10^3
10^4
10^5

Figure 6

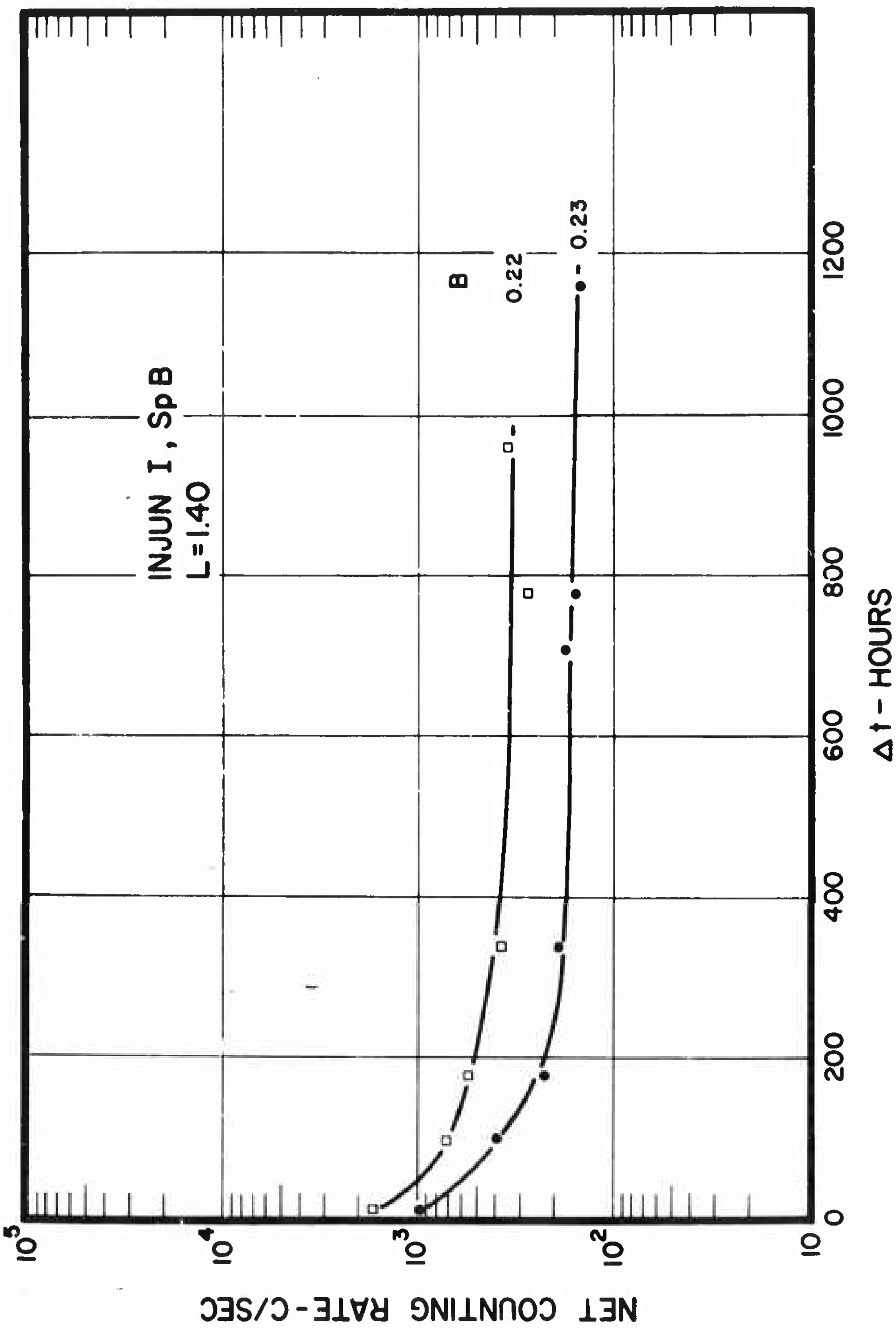
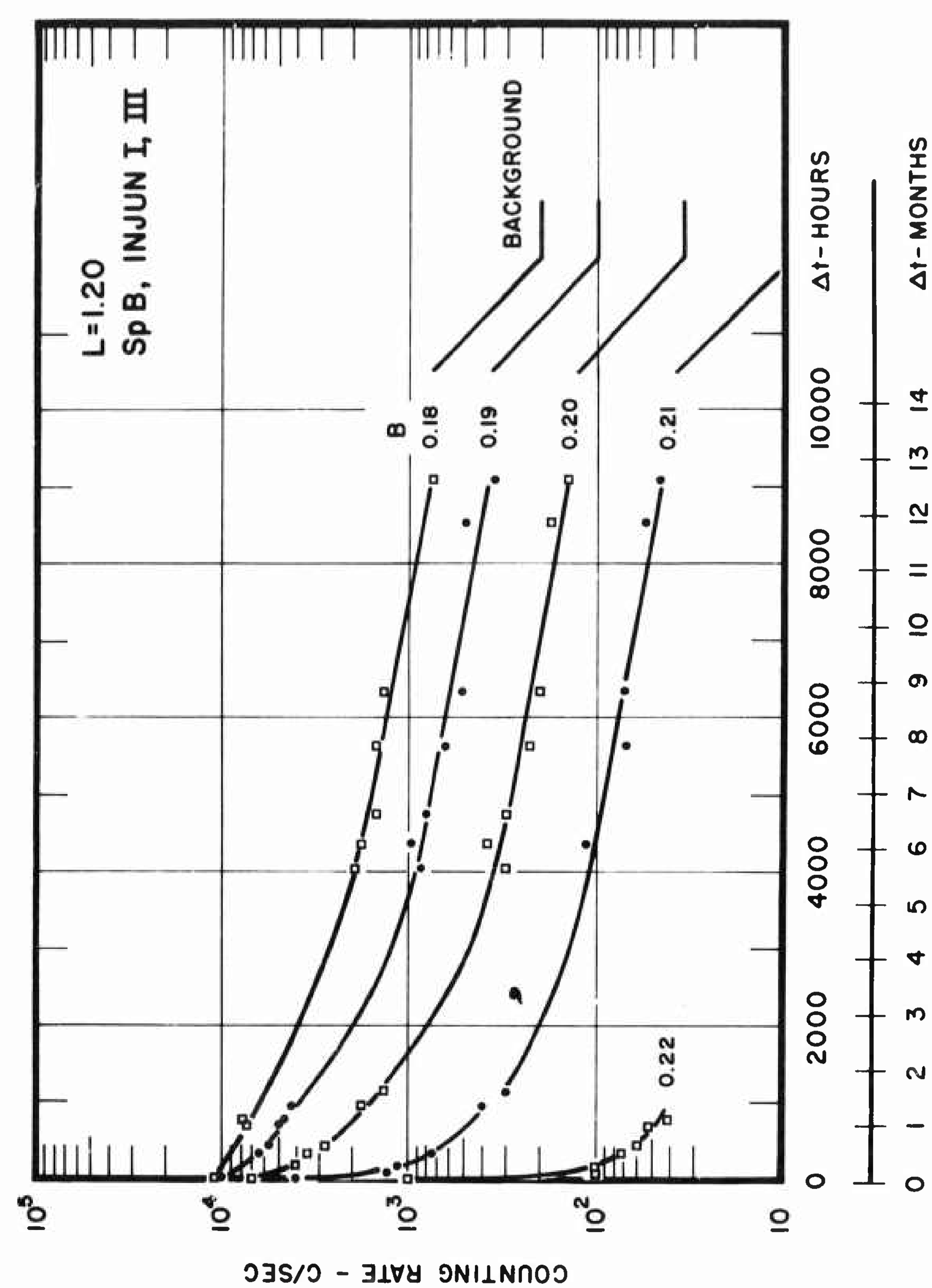

INJUN I, Sp B
L=1.40
B
0.22
0.23
NET COUNTING RATE - C/SEC
Δt - HOURS
0
200
400
600
800
1000
1200
10
10^2
10^3
10^4
10^5

Figure 7



L=1.20
Sp B, INJUN I, III
BACKGROUND
B
0.18
0.19
0.20
0.21
0.22
COUNTING RATE - C/SEC
Δt - HOURS
Δt - MONTHS

Figure 8

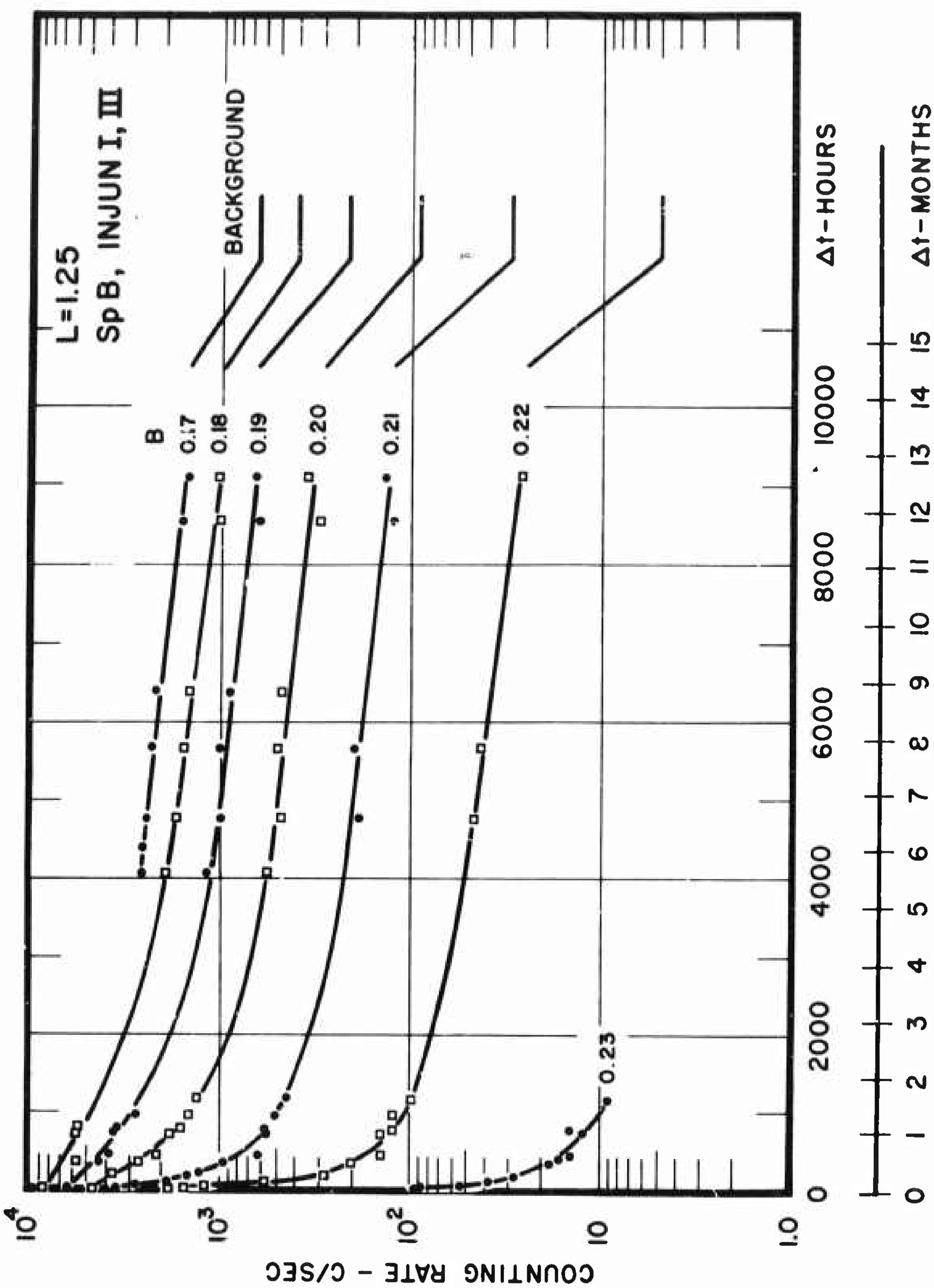

L=1.25
Sp B, INJUN I, III
BACKGROUND
B
0.17
0.18
0.19
0.20
0.21
0.22
0.23
Δt-HOURS
Δt-MONTHS
COUNTING RATE - C/SEC

Figure 9

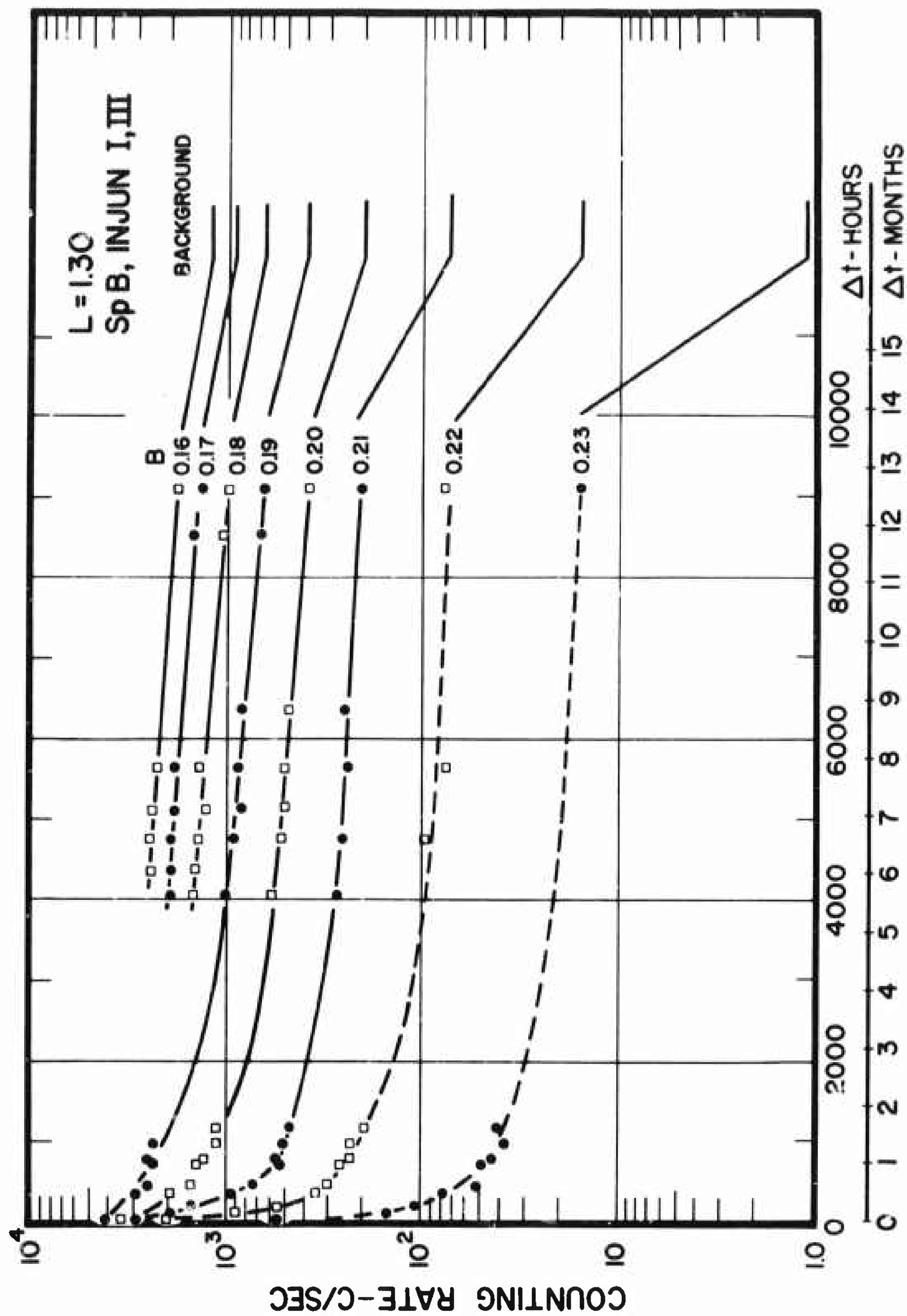

L = 1.30
Sp B, INJUN I, III
BACKGROUND
B
0.16
0.17
0.18
0.19
0.20
0.21
0.22
0.23
COUNTING RATE-C/SEC
Δt - HOURS
Δt - MONTHS

Figure 10

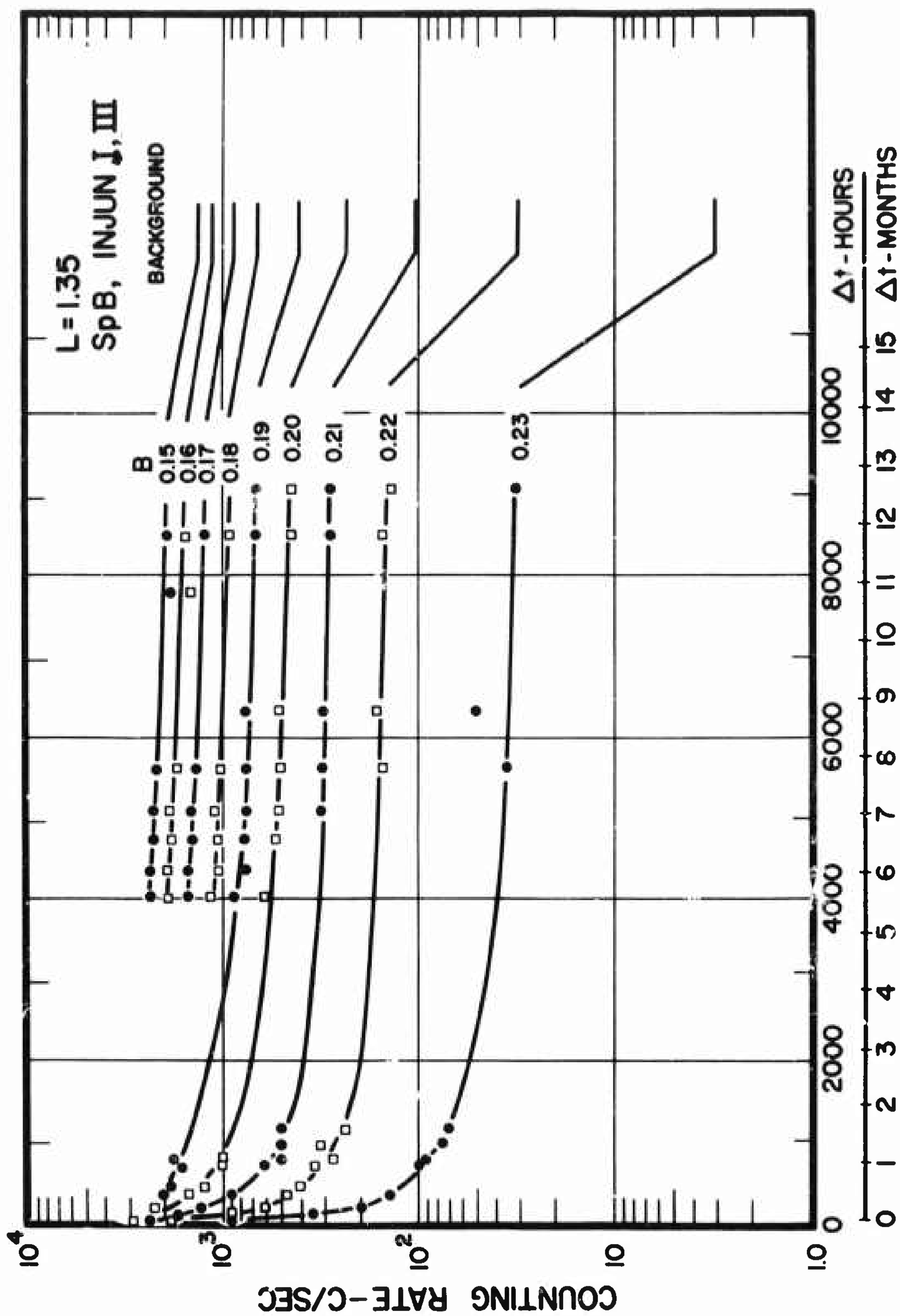
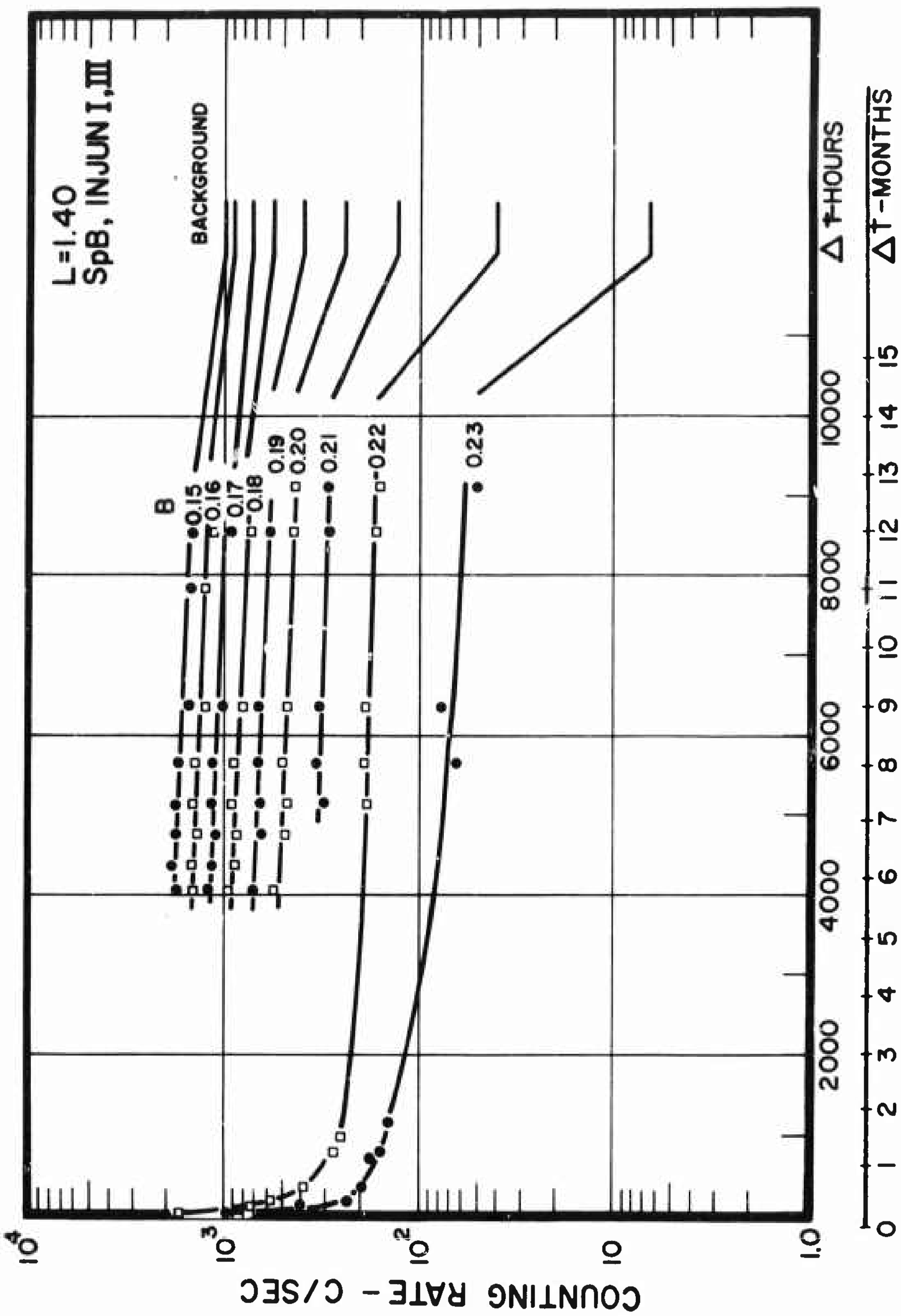

L = 1.35
SpB, INJUN I, III
BACKGROUND
B
0.15
0.16
0.17
0.18
0.19
0.20
0.21
0.22
0.23
Δt - HOURS
Δt - MONTHS
COUNTING RATE - C/SEC

Figure 11



L=1.40
SpB, INJUN I,III
BACKGROUND
B
0.15
0.16
0.17
0.18
0.19
0.20
0.21
0.22
0.23
COUNTING RATE - C/SEC
10^4
10^3
10^2
10
1.0
0
2000
4000
6000
8000
10000
Δ T-HOURS
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Δ T-MONTHS

Figure 12

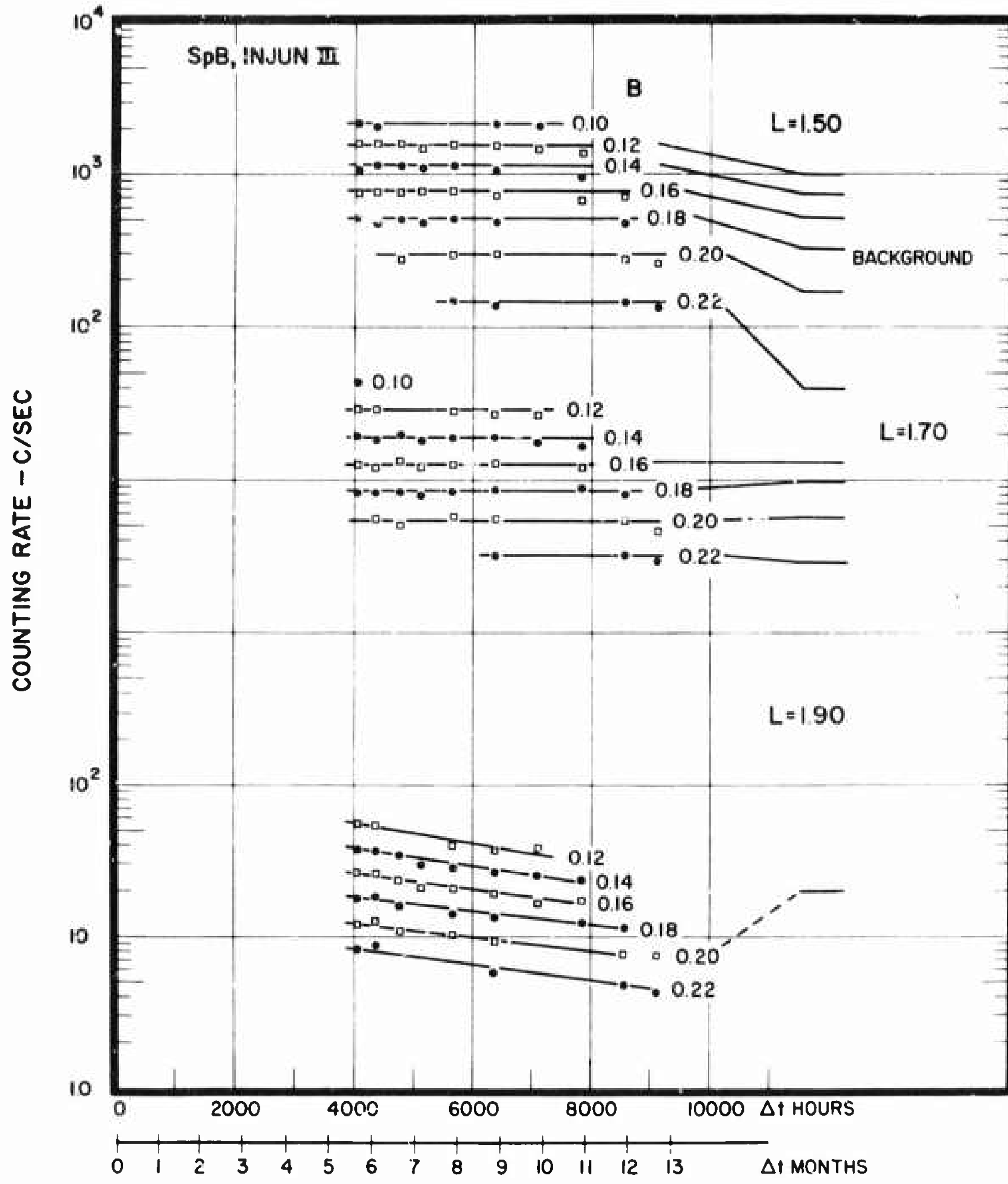
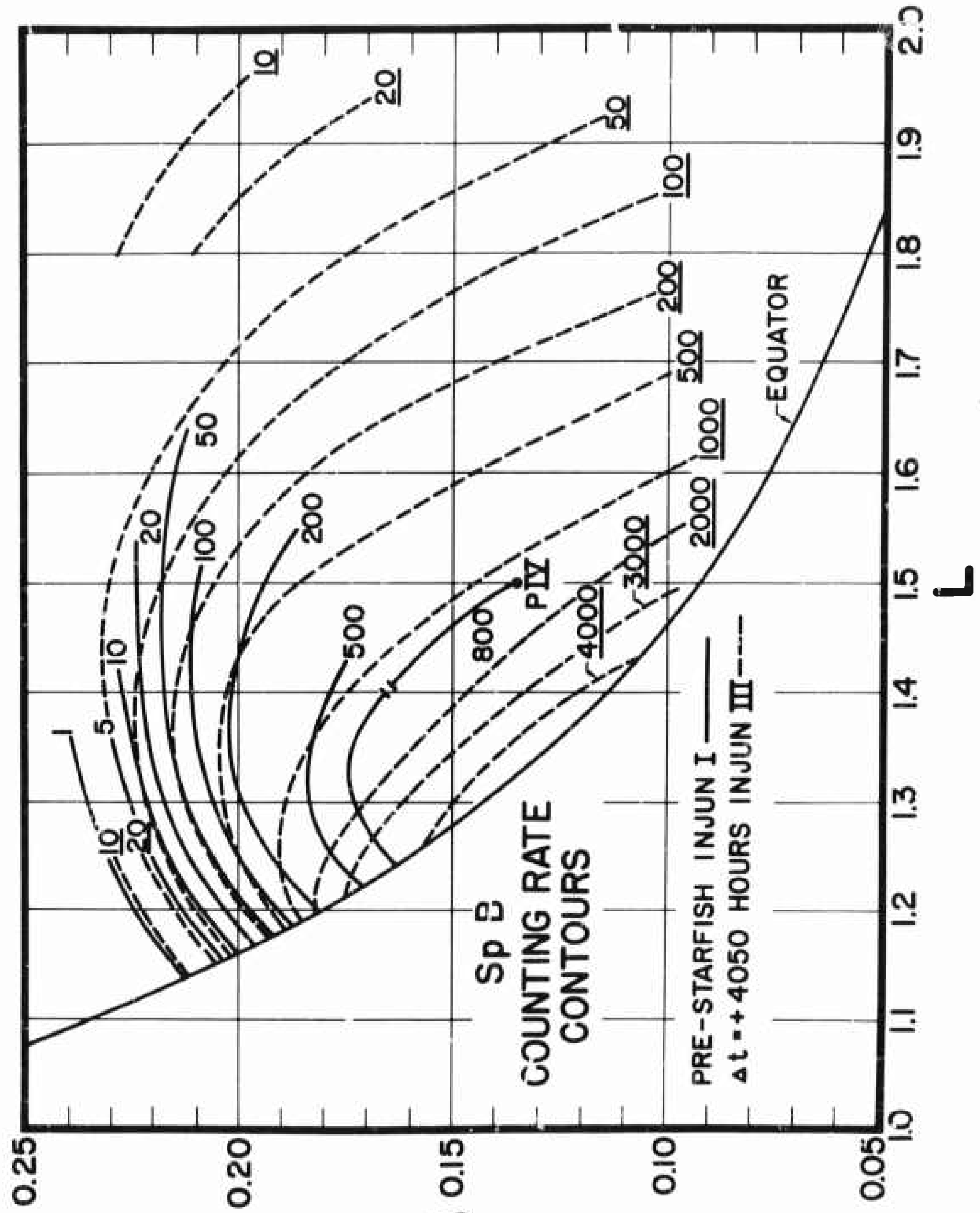

SpB, INJUN III
B
L=1.50
0.10
0.12
0.14
0.16
0.18
0.20
0.22
BACKGROUND
L=1.70
L=1.90
COUNTING RATE – C/SEC
0
2000
4000
6000
8000
10000
Δt HOURS
Δt MONTHS

Figure 13



Sp B
COUNTING RATE
CONTOURS
PRE-STARFISH INJUN I
Δt = +4050 HOURS INJUN III
EQUATOR
P IV
B
L
0.25
0.20
0.15
0.10
0.05
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
1
5
10
20
50
100
200
500
800
10
20
50
100
200
500
1000
2000
3000
4000

Figure 14

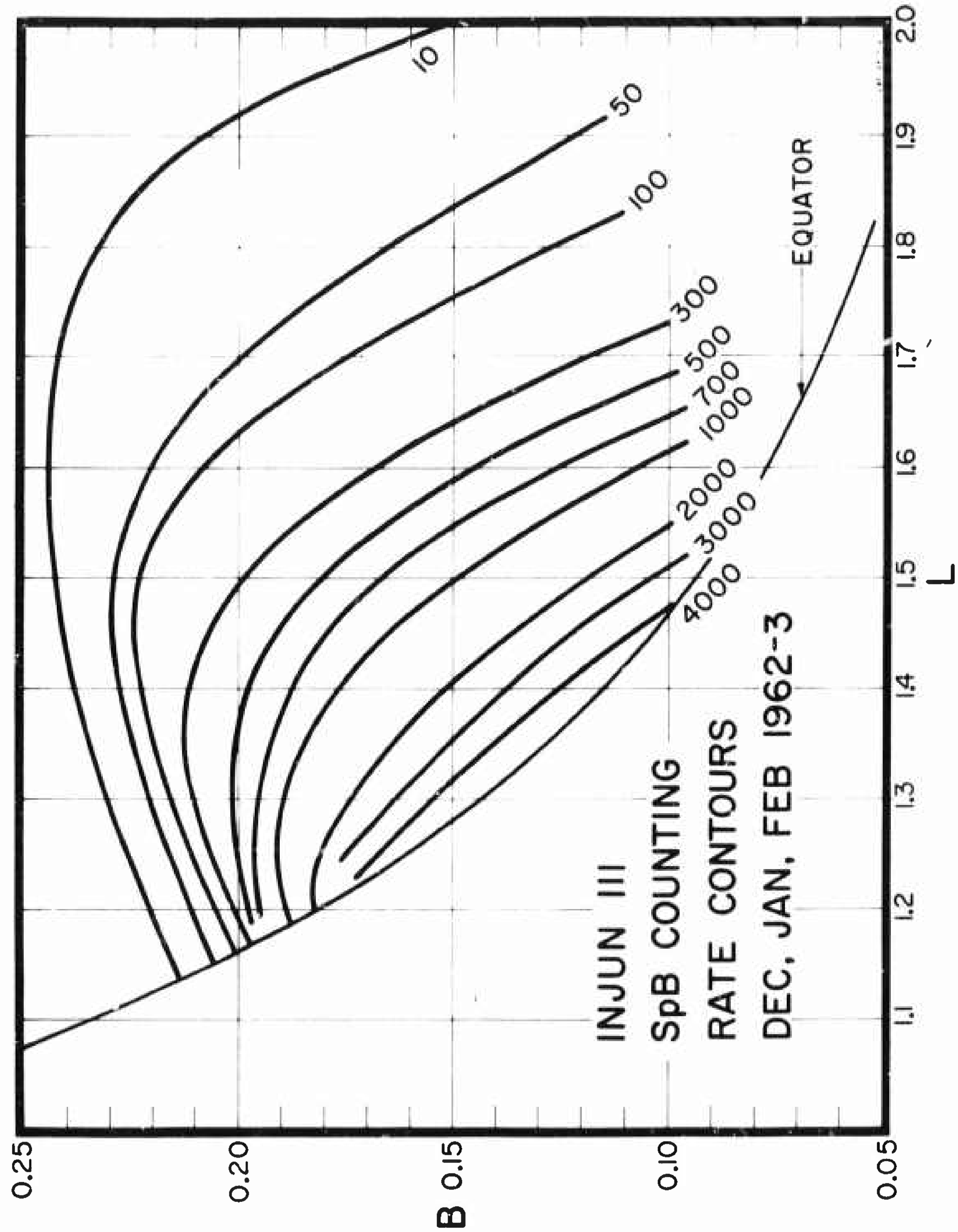

INJUN III
SpB COUNTING
RATE CONTOURS
DEC., JAN., FEB 1962-3
EQUATOR
10
50
100
300
500
700
1000
2000
3000
4000
B
0.25
0.20
0.15
0.10
0.05
L
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0

Figure 15

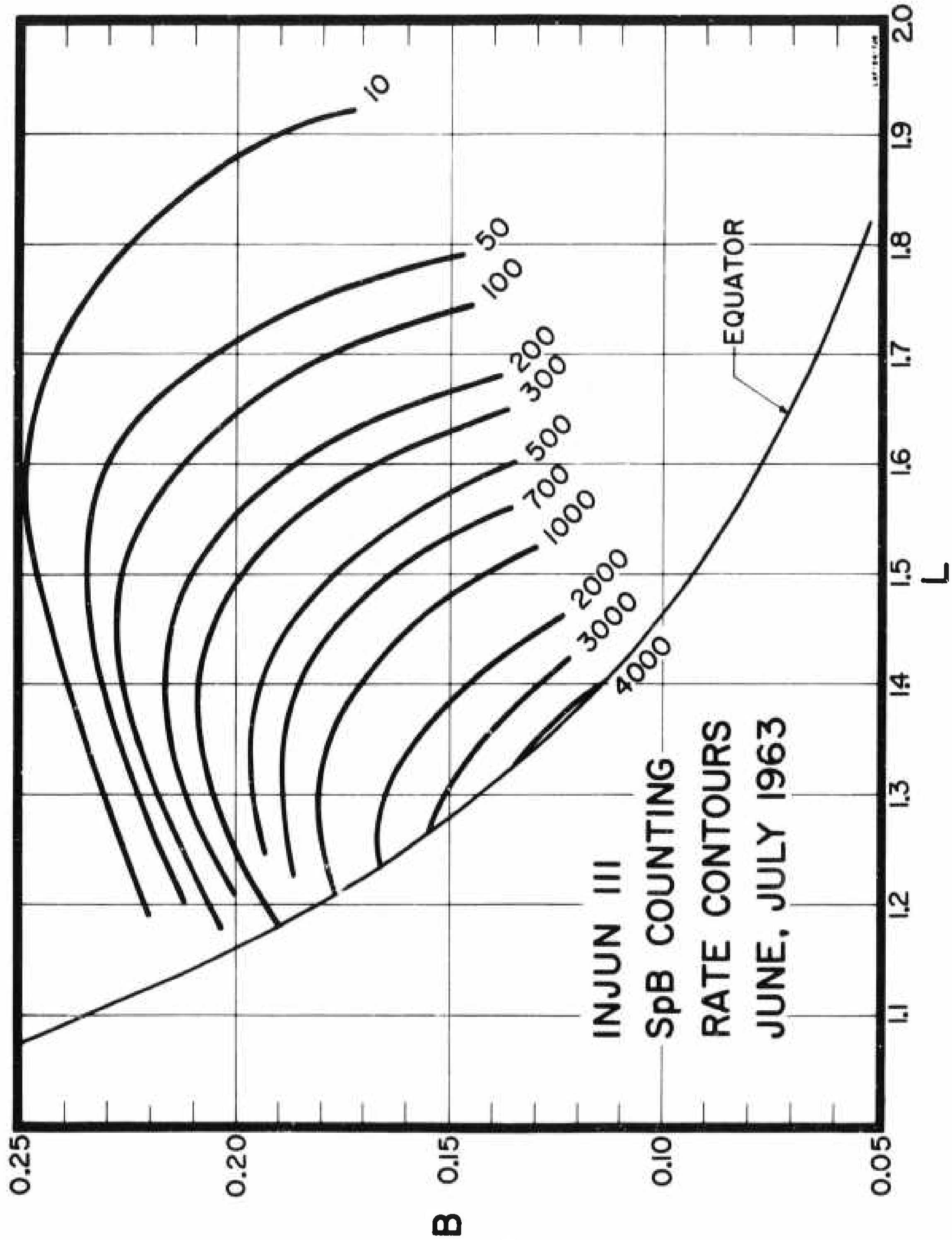

INJUN III
SpB COUNTING
RATE CONTOURS
JUNE, JULY 1963
EQUATOR
10
50
100
200
300
500
700
1000
2000
3000
4000
L
B
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
0.25
0.20
0.15
0.10
0.05

Figure 16

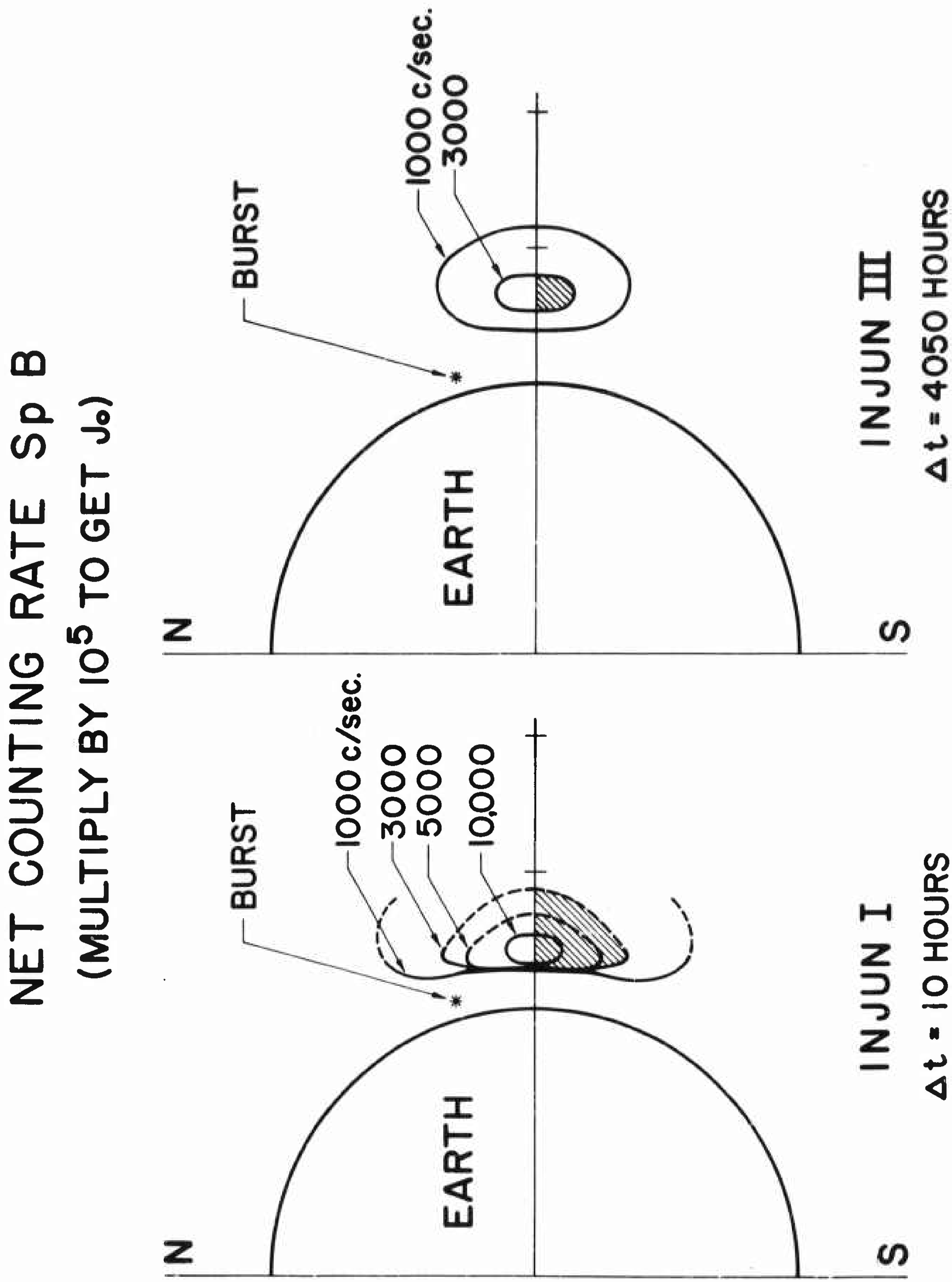

NET COUNTING RATE Sp B
(MULTIPLY BY 10⁵ TO GET J₀)
N
EARTH
S
BURST
1000 c/sec.
3000
5000
10,000
INJUN I
Δt = 10 HOURS
N
EARTH
S
BURST
1000 c/sec.
3000
INJUN III
Δt = 4050 HOURS

Figure 17

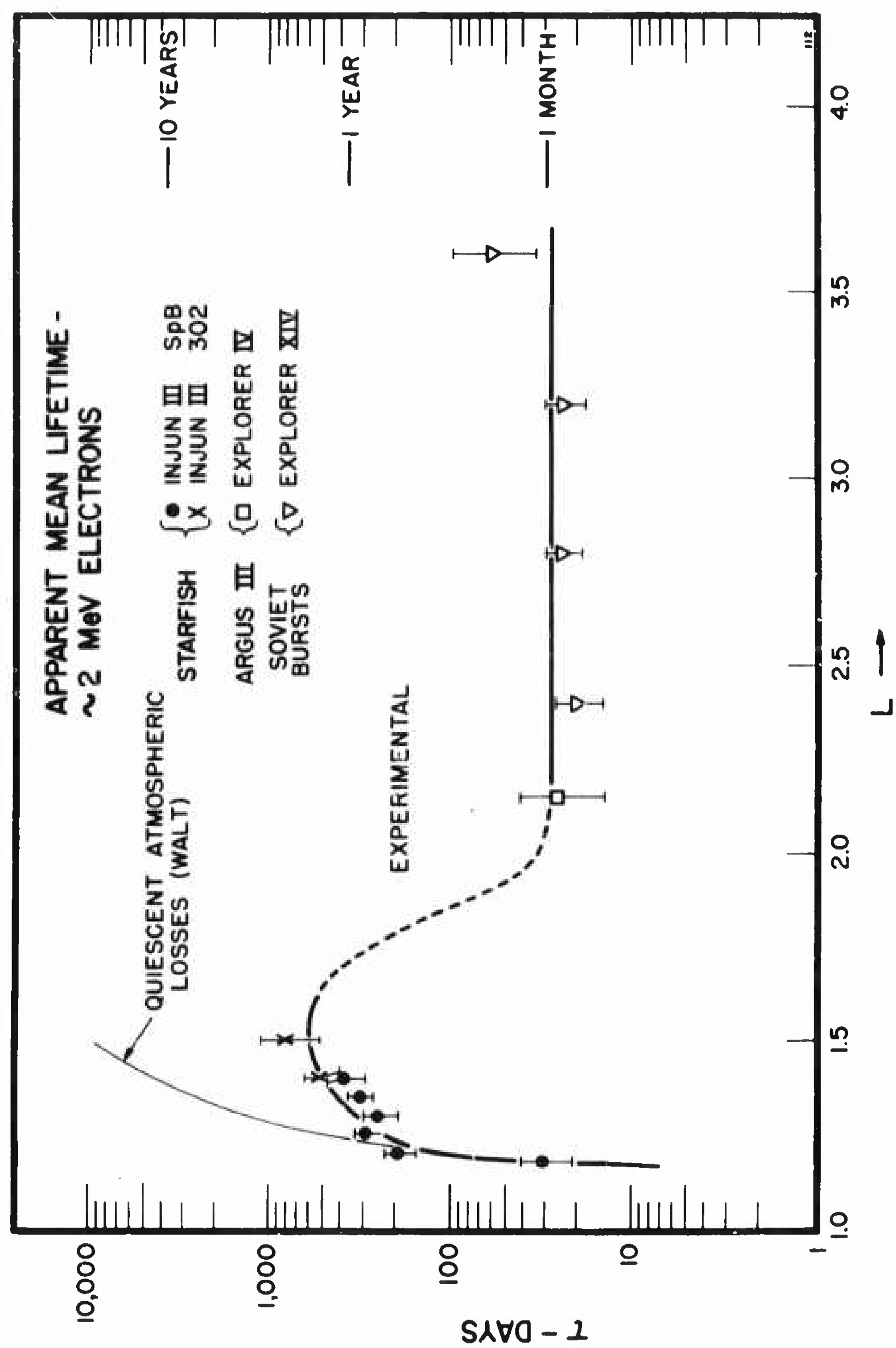

APPARENT MEAN LIFETIME -
~2 MeV ELECTRONS
STARFISH
INJUN III SpB
INJUN III 302
ARGUS III
EXPLORER IV
SOVIET BURSTS
EXPLORER XIV
QUIESCENT ATMOSPHERIC LOSSES (WALT)
EXPERIMENTAL
10 YEARS
1 YEAR
1 MONTH
10,000
1,000
100
10
1
1.0
1.5
2.0
2.5
3.0
3.5
4.0
L
τ - DAYS

Figure 18

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* University of Iowa, Department of Physics and Astronomy	**2a. REPORT SECURITY CLASSIFICATION** UNCLASSIFIED **2b. GROUP**

3. REPORT TITLE

Spatial Distribution and Time Decay of the Intensities of Geomagnetically Trapped Electrons from the High Altitude Nuclear Burst of July 1962

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

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5. AUTHOR(S) *(Last name, first name, initial)*

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	Office of Naval Research

13. ABSTRACT

A one-year observational study of the artificial radiation belt produced by the nuclear burst Starfish on 9 July 1962 is reported. It is estimated that 1.3×10^{25} electrons from radioactive fission products, or some 2.6% of the total yield, were present in geomagnetically trapped orbits at 10 hours after the burst. These electrons disappeared in the manner expected from the atmospheric loss theory of Walt for values of the magnetic shell parameter $L < 1.25$ earth radii. At increasing values of L the rate of disappearance was progressively more rapid than expected by this theory. The maximum observed value of the apparent mean lifetime of ~ 2 MeV electrons in the time range $4000 < \Delta t < 10{,}000$ hours was 2 years at $L = 1.5$. About 15% of the initially injected electrons (or 0.4 of 1% of the total) survived the first 5 1/2 months, about 10% the first year.

Detailed spatial distribution and temporal data are given in a series of plots.

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